The Use of a Permanent Magnet for Water Content Measurements of Wood Chips

P. J. Barale, C. G. Fong, M. A. Green, P. A. Luft, A. D. McInturff, J. A. Reimer, and M. Yahnke

***Abstract*—The Lawrence Berkeley National Laboratory has developed a device that measures the water content of wood chips, pulp and brown stock for the paper industry. This device employs a permanent magnet as the central part of a NMR measurement system. This report describes the magnet and the NMR measurement system. The results of water content measurements in wood chips in a magnetic field of 0.47 T are presented.**

***Index Terms*—NMR, permanent magnet, pulp and paper.**

I. Introduction

THE LAWRENCE Berkeley National Laboratory (LBNL) has been involved with developing sensors for the paper industry since 1997. The industry has been modernizing its facilities to improve efficiency. Modern paper plants recycle water, pulp, digester chemicals, and the chemicals that provide the paper finish. A modern paper plant can be a net energy producer. The organic material that is separated from the cellulose (lignin and other volatile chemicals) during the pulping process is used to generate heat for producing steam and electricity for use within the plant. The amount of net energy produced by the plant depends on the plant efficiency and the amount of feedstock wood that enters the mill.

Modern paper plants can produce over 1500 metric tons of paper per day on a single production line. These plants use continuous pulping. This means that wood in the form of chips, water, and chemicals enter the digester on a continuous bases. A slurry of cellulose and water (brownstock) leaves the digester to go to a bleaching plant or directly to a paper-making machine. The black liquor left over from the pulping process is separated into recycled pulping chemicals and organic fuel used to generate energy for the mill. The LBNL program worked on developing nuclear magnetic resonance (NMR) sensors that could monitor the pulping process [1].

LBNL developed a bench scale sensor that measures the water content of wood chips, brownstock, and black liquor. This report describes a water content measurement device that uses a permanent magnet. Moisture content measurements were made using ordinary hydrogen NMR at 20 MHz. The results of the measurements of water content in wood chips is presented in this report.

Manuscript received September 26, 2001. This work was supported by the Office of Industrial Technologies, United States Department of Energy under DOE Contract DE-AC03-76SF00098. This work was performed at the Lawrence Berkeley National Laboratory.

The authors are with the Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA.

Publisher Item Identifier S 1051-8223(02)03869-1.

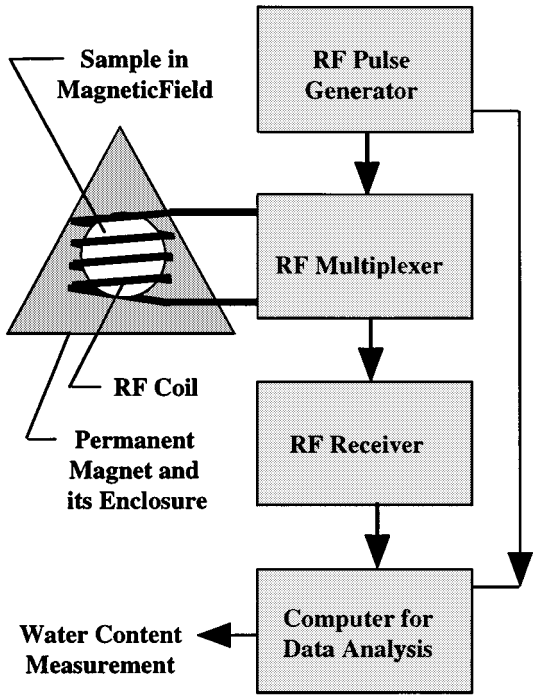

Fig. 1. A schematic diagram of a wood chip moisture content measurement device that uses NMR.

II. The NMR Moisture Measurement Device

The NMR moisture measurement device consists of a permanent magnet, the magnet enclosure, a tube for carrying the product to be measured, an RF coil that sends and receives the RF pulses for doing the NMR measurements, an RF pulse generator, an RF receiver and a computer that analyzes and reformulates the data. A schematic diagram of the water content measurement device that uses NMR is shown in Fig. 1.

The NMR magnet is a permanent magnet that was purchased from a commercial vendor. This magnet produces an induction of 0.47 T that is uniform to about 10 parts per million. The good field diameter is about 19 mm, and the good field region length is about 25 mm. The magnet has a triangular shape. The permanent magnet is about 322 mm long and 282 mm wide and 197 mm thick. The magnet mass is 68 kg. A schematic view of the 0.47 T permanent magnet is shown in Fig. 2.

The magnet shown in Fig. 2 uses oriented samarium–cobalt blocks to generate the magnetic field in the 36.1-mm gap. The magnet has machined iron poles that are carefully shimmed in place to achieve the desired field uniformity in the good field region. Measurements of the gap field at LBNL showed that the

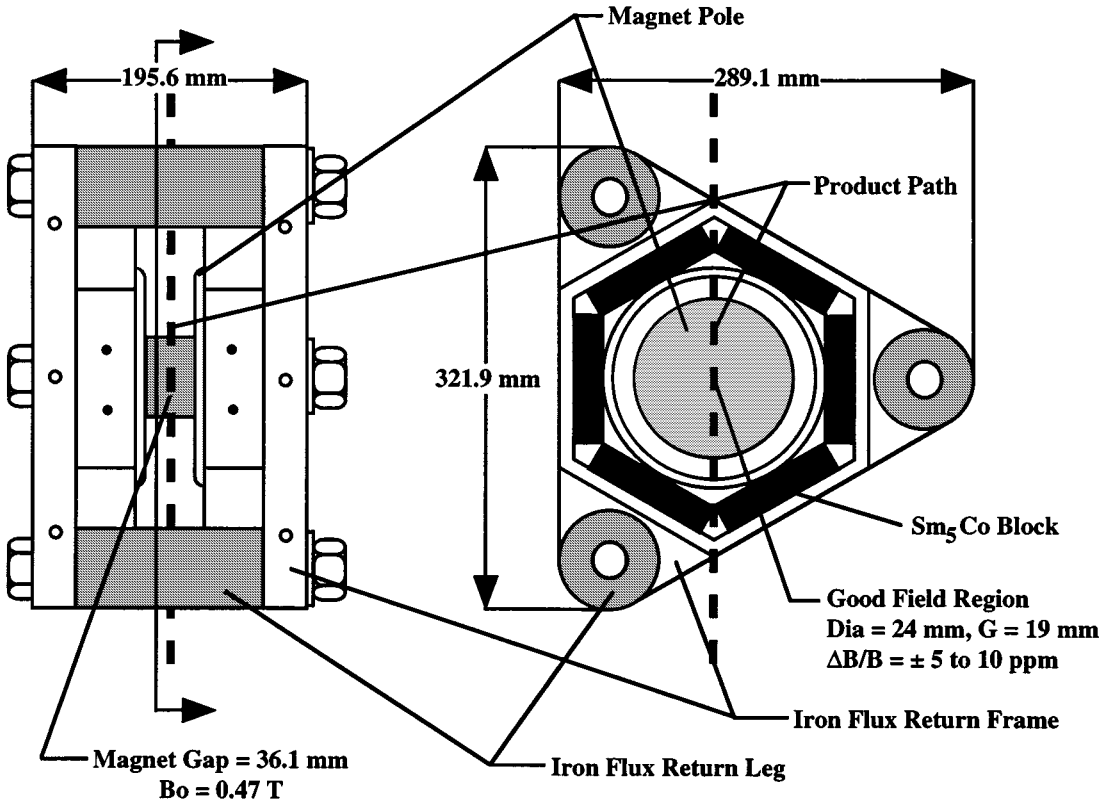

Fig. 2. A schematic view of the 0.47 T permanent magnet used in the bench scale NMR moisture measurement device.

field uniformity was very close to that claimed by the manufacturer.

The biggest problem with using permanent magnets for NMR is the change in field due to temperature changes. Samarium–cobalt is one of the best of the permanent magnet materials with a temperature coefficient of −400 parts per million (ppm) per degree C. As a comparison neodymium–iron has a temperature coefficient of about −1000 ppm per degree C and the ferrite materials have a temperature coefficient close to −2000 ppm per degree C. The temperature coefficient of the permanent magnet materials can be particularly troublesome when one is using NMR to measure moisture content. LBNL solved the temperature coefficient problem by putting the permanent magnet into an insulated temperature-controlled box.

The use of the permanent dipole permitted LBNL to use a solenoidal RF coil that was wrapped around the sample tube. The sample tube and the RF coil insulation were made from a material that does not contribute to the NMR signal. The arrangement of the RF coil and sample is shown in Fig. 3.

Since the field generated by the magnet is 0.47 T, the RF system designed for a nominal frequency of 20 MHz. The proof of principal laboratory tests were done at 300 MHz in a 7.1 T superconducting solenoid with a very uniform (about 0.1-ppm field). The superconducting magnet had virtually no field drift and no temperature coefficient. The wood samples in the bench scale magnet tests were two to three orders of magnitude larger than they were in the 300 MHz laboratory tests. It was determined that good NMR signals could be obtained in the 0.47 T permanent magnet.

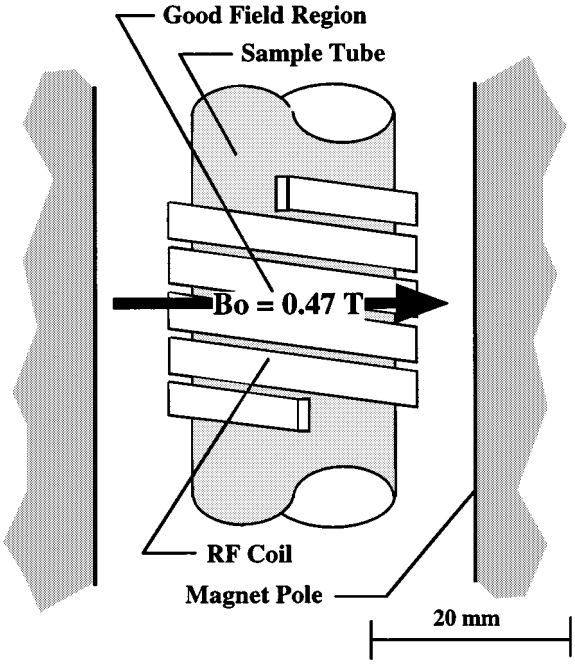

Fig. 3. Arrangement of the wood chip sample tube and the RF coil within the 0.47 T permanent magnet gap.

The liquid water signal was separated from the signal generated by the cellulose and lignin in the wood using free induction decay (FID) of the RF signal that was read back from the sample. The solid components in the wood have a short FID decay time constant while the liquid water has a long FID decay time con-

stant. The FID signal shows a characteristic knee between the short time constant decay of the solid wood and the long time constant decay of water. Using that characteristic signal, one can determine the mass fraction of liquid water in the sample.

III. Moisture Content Measurements of Wood Chips Using NMR in a Permanent Magnet

LBNL successfully measured the water content of wood chips, brownstock (a mixture of cellulose and water) and black liquor using the bench scale prototype. Wood chip water-content tests were done over a broad range of moisture contents for various species of wood. NMR measurements of moisture content were compared with the TAPPI standard method of measuring moisture content where the mass of the sample is measured before and after oven drying at reduced pressure. A comparison of moisture content measured by NMR and oven drying is shown in Fig. 4.

Fig. 4 compares measurement made on two different samples of wood chips. From Fig. 4, one can see that moisture content measurements made using NMR at 20 MHz are in good agreement with moisture content measurements made using the standard TAPPI test employing oven drying. The measurement points are within a few percent of the straight line that indicates perfect agreement between the two methods of measurement. It is not clear whether the errors are due to errors in the NMR measurement system or errors in oven drying method. The biggest difference between the measurement methods is the time that it takes to make a single moisture content measurement. A single NMR water content measurement takes only a few seconds; water content measurements using oven drying take up to two hours.

NMR does more than just measure the moisture content of wood. It can also tell one where the moisture is located in the sample. Samples of varying moisture content were prepared from previously dried chips and water. The samples were allowed to come to equilibrium by sitting in contact with the water for over 24 hours. NMR was used to measure the water in the pores and the water on the surface. Fig. 5 shows the results of these measurements.

Fig. 5 strongly suggests that the pores in the wood species measured saturate, when the moisture content reaches about 60 percent. Water will soak into the wood until the pores are saturated. Once the pores are saturated, the excess water remains on the surface. It is clear from Fig. 5 that NMR can differentiate between liquid water within the wood pores and liquid water outside of the wood pores.

Since water outside of the wood pores can be differentiated from water within the pores, experiments were done to see if water in liquid form could be differentiated from water in solid form within wood chips. A series of measurements were done with wood chips with varying water contents at a series of temperatures from −50 C to +20 C. Fig. 6 shows some results taken for chips of varying moisture contents at −20 C and +20 C.

The first thing that was surprising about the frozen chip data was the fact that frozen water could be differentiated from wood solids and liquid water. It was thought that water in the

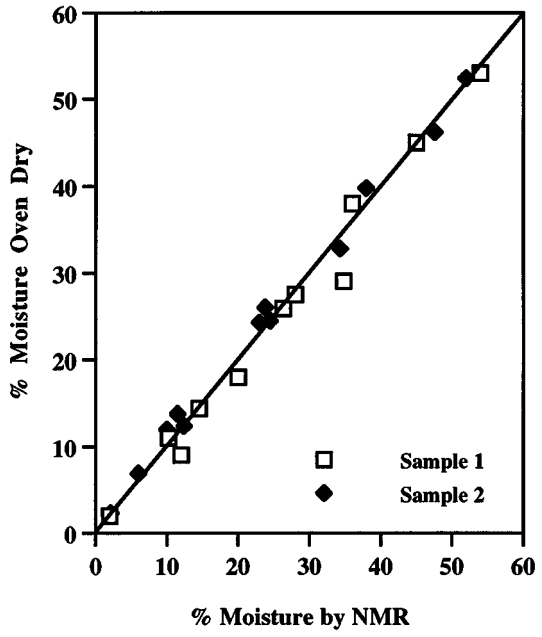

Fig. 4. A comparison of the measurement of moisture content in wood chips using NMR and oven drying.

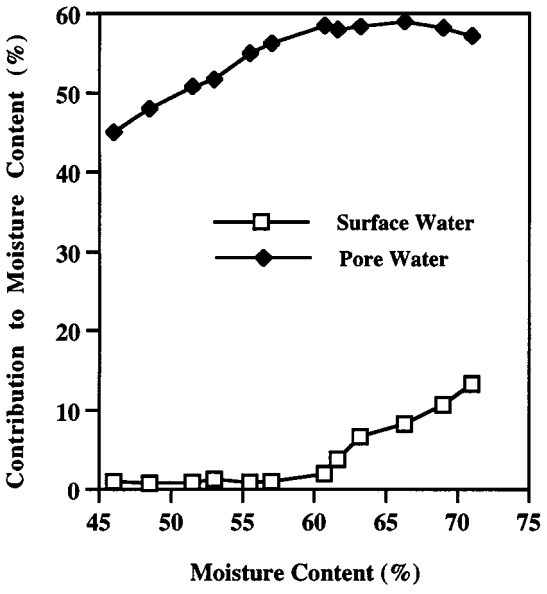

Fig. 5. Moisture content within wood pores and on the surface of the chips as measured using NMR at 20 MHz.

form of ice should have a FID decay time constant that is similar solid wood. The measurements show that the FID time constants could be differentiated between wood, water ice, and liquid water. The second thing of interest was that a certain fraction of the water in wood chips remained in the chips in liquid form, even at −50 C. At −20 C, much of the water in the chip pores appears to be liquid. The cause of this is not understood. The water within the wood pores is quite pure so a suppressed freezing point due to dissolved salts is an unlikely cause the liquid water found in the wood pores at temperatures below 0 C.

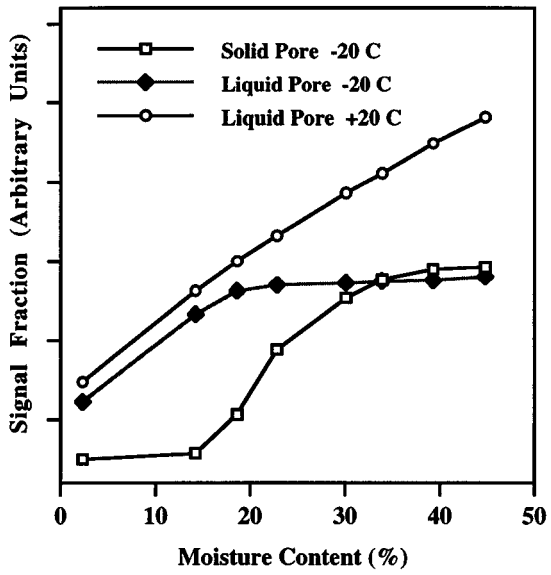

Fig. 6. A measure of the amount of liquid water and solid water in the pores of wood chips at +20 C and −20 C.

IV. Concluding Comments

The experiments at LBNL indicate that the water content of wood chip, pulp, and paper can be measured using NMR at relatively low fields. Other experiments not reported in this report indicate that water content can also be measured in brownstock and black liquor from the digester of a paper mill [2].

Moisture content measurements can be done accurately using NMR. It appears that NMR measurements of moisture content may be as accurate as measurements made using the TAPPI standard test for moisture content. NMR moisture content measurements can be made in a few seconds.

NMR moisture content measurements can differentiate between pore moisture and surface moisture. Moisture in the form of liquid water can be differentiated from water in the form of ice. Being able to differentiate water from ice means that NMR can be used in a number of areas in the forest products industry. The important question is whether NMR sensors will be cost effective.

The bench scale model tested at LBNL could be the basis for a laboratory moisture content tester for use within a paper mill. The effect of the permanent magnet temperature coefficient can be overcome by automatically tuning the RF frequency so that it is always on resonance.

Increasing the sample size to allow the flow stream entering a plant to be analyzed will require a much larger good field region (about 150 mm in diameter) than can be economically achieved using a permanent magnet. A good field region that is 150 mm in diameter will probably need a superconducting magnet to generate the magnetic field [2].

References

[1] D. Capitani, A. L. Segre, D. Attanasio, and B. Blicharska *et al.*, "H-1 NMR relaxation study of paper as a system of cellulose and water," *TAPPI Journal*, vol. 79, no. 6, p. 113, June 1996.

[2] M. A. Green, P. J. Barale, and C. G. Fong *et al.*, "Magnet options for sensors for the pulp and paper industry," in Advances in Cryogenic Engineering. New York: AIP Press, 2001, vol. 47, to be published.